



# Impact of ski piste management on mountain grassland ecosystems in the Southern Alps

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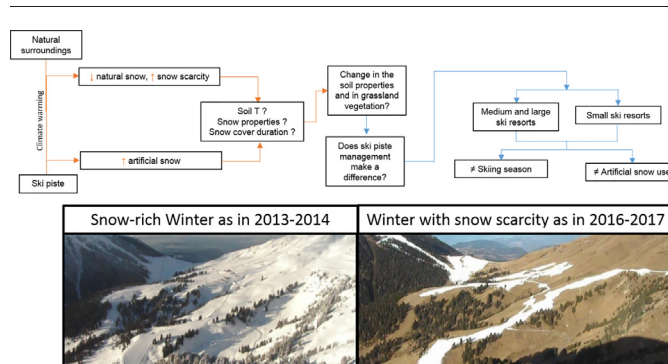
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## HIGHLIGHTS

- Soil and snow parameters differed strongly between ski pistes and surroundings.
- In absence of natural snow soil freezing was as frequent as under artificial snow.
- The share of plant functional groups and plant richness was differentiated.
- The impact on vegetation is much stronger in medium compared to small ski areas.

## GRAPHICAL ABSTRACT



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## ABSTRACT

In the Southern Alps, climate warming induced the use of artificial snow since two decades. In this area, two different ski piste management practices prevail: (1) large and medium ski resorts (M), which guarantee a ski season of four to five months using artificial snow, whereas (2) in the small, local ski resorts (S) it usually lasts two or three months. Our research addresses two main questions: 1) what is the impact of the ski pistes on the physico-chemical properties of the snow, on the soil and on the vegetation of mountain grassland ecosystems and 2) does the impact on the mountain grassland ecosystems change between medium and small ski resorts? Our experimental approach follows a pairwise design of plots on mountain grasslands of the ski pistes and control plots on mountain grasslands outside the pistes, where we examined the snow and soil properties and the vegetation composition. Under the long ski-season management (M) we found a significantly lower soil temperature below the snow cover of the ski pistes than the one below the natural snowpack, but this difference was limited to the period of natural snow cover. Only in M, pistes showed a lower biomass production and species richness in the mountain grassland plant communities compared to the controls, while there was no effect in S. The proportions of plant functional groups' cover changed in both ski resort types between piste and control. The most important factors affecting the observed differences in vegetation between pistes and controls were snow duration, snow and soil chemical properties, with more marked differences in the soil properties in M respect to S. The study concludes that reducing the ski season's length, therefore limiting the artificial snow's input, as in S, is more adequate to minimize the environmental impact in a changing climate.

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## 1. Introduction

Vestergren wrote in 1902 that the most important variable affecting the vegetation patterns in alpine regions is snow (Vestergren, 1902, reported by Walker et al., 2001). Snow plays a fundamental role in protecting plants from extremely low temperatures, frost damage, winter desiccation, mechanical damage (wind, skiers) and solar radiation (Walker et al., 2001; Körner, 2003). In addition, snow regulates winter tourism, mostly ski tourism. The already observed warmer temperatures during the last decades (IPCC, 2014) forced ski area operators to increase the use of artificial snow, which guarantees the ski season. In South Tyrol (Italy), 59% of the ski slopes are covered with artificial snow (Teich et al., 2007). Artificial snow, together with the ski-slope preparation, has a considerable effect on the landscape, in terms of water and energy consumption, soil erosion, it delays the plants' phenology and can change the species and functional group composition and lower species richness and diversity (Kammer, 2002; Rixen et al., 2003; Wipf et al., 2005; Roux-Fouillet et al., 2011). Moreover, a lower diversity of carabids, spiders and grasshoppers on ski pistes compared to natural sites have been reported (Negro et al., 2010). There are also potential conflicts between the avifauna and future ski piste distribution following climate change (Brambilla et al., 2016). In this context of climate change, alpine ecosystems are exposed to novel challenges, i.e. alterations of the natural snowpack as well as increasing use of artificial snow cover.

To build ski pistes, both artificial and natural snow need to be compacted reducing the thickness and increasing the density of the snow cover (Sturm et al., 1997). This compaction, in turn, decreases the insulation capacity of the snowpack, which may cause ground freezing, while the temperature of the ground under the uncompacted snow remains constant at 0 °C (Rixen et al., 2004). While extant research established lower soil temperatures under artificial than under natural snow cover (Rixen et al., 2004), it remains unclear which scenario would appear in years of natural snow scarcity. Moreover, the addition of artificial snow and its compaction delay the snow melting time of several days (17 in average, according to Rixen et al., 2003), shortening the growing season (Wipf et al., 2005). It is well known that the time of snowmelt plays an important role in regulating plants distribution and productivity, in addition to soil pH and moisture (Gjærevoll, 1956, reported by Walker et al., 1994; Billings and Bliss, 1959; Walker et al., 2001). Magnani et al. (2017) reported that the summer soil temperature is negatively correlated to the duration of the snow cover. According to these authors, the lower soil temperature during the growing season reduces soil nitrogen (N) (Magnani et al., 2017). In turn, if the N supply is altered, the carbon (C) flux and the leaf development may be affected (Schimel et al., 2004). Also Gros et al. (2004) recorded lower C and N content on the pistes compared to natural control sites. In addition, the water used for snowmaking usually has a composition that differs from that of the natural snow: it may contain more nutrients and may have a different pH, and this extra input of minerals may increase the soil pH and the soil electrical conductivity (EC) on the ski pistes (Wipf et al., 2005; Delgado et al., 2007; Meijer zu Schlochtern et al., 2014), changing the habitat conditions for plant species (Kammer, 2002; Allegrezza et al., 2017). Higher temperatures due to climate change may contribute to an increase of rainfall precipitation instead of snow. This reduces the snow cover and increases its density, because the liquid-water content increases in respect to volume (Cagnati, 2003). Consequently, the snow porosity decreases, the insulation capacity of the snow drops, and the thermal conductivity increases, allowing the less insulated ground to freeze (Venalainen et al., 2001). In this view, the continuous presence of the artificial snow may compensate the snow lack, preventing soil frost (Rixen et al., 2003). Furthermore, in case of absence of the snow cover, some plants can suffer of "drought-related winter stress" (Tahkokorpi et al., 2007) and artificial snow may mitigate that effect. Moreover, in case of snow lack or snow

scarcity, the increased artificial snow depth protects plants against mechanical damage (Newesely and Cernusca, 1999).

In South Tyrol (N-Italy), located in the South-Alpine area, two different ski-piste management practices prevail. They differ in the duration of the snow cover and in the intensity of ski piste preparation and skiing. Large and medium regional ski resorts (M) guarantee a ski season of four to five months by using artificial snow. Small, local ski resorts (S) make a limited use of the artificial snow; they rely more on natural snow availability and their ski season usually lasts for only two or three months. The majority of all the previously cited studies on the effects of ski slopes on vegetation has been carried out in big ski resorts in Europe (Kammer, 2002; Rixen et al., 2004; Wipf et al., 2005; Roux-Fouillet et al., 2011). In South Tyrol, besides the four large and medium regional ski resorts, there are 38 small ski areas. Their management practices differ from those of the large and medium ski areas because their resources are more limited (both with regard to social and economic capital) and they focus mainly on the local inhabitants instead on the tourists.

The winter 2016–2017, in South Tyrol, was particularly dry and it well represents the snow-lacking part of the inter-annual variability of snow cover regimes predicted by global warming models (Groisman and Davies, 2001). In fact, the total amount of precipitations registered in January, February and March 2017 was 38.5 mm, whereas the recording during the same period of the previous decade (2006–2016) was on average 91.7 mm (Autonomous Province of Bozen-South Tyrol, 2017). The lack of snow had a double effect: 1) it forced the operators on the ski slopes to a frequent/intensive use of artificial snow, whose properties could differ from those of the natural snow and 2) the natural surroundings were without snow protection for the soil, which may affect soil properties and, as a consequence, vegetation. Thus, the winter 2016–2017 can be considered as a "natural experiment" to investigate differences in soil temperature under a scenario of scarce or absent natural snow compared to an artificial snow cover, which will be more common in future (IPPC, 2014). In fact, according to Abegg et al. (2007), because of the expected increase in annual mean temperature, "the number of naturally snow-reliable ski areas in the Alps could drop to 500 (75 % of the current Alpine ski areas) with a 1 °C warming, to 404 (61 %) with a 2 °C warming and to 202 (30 %) with a 4 °C warming" and our study can give an overview of the possible implications on the ecosystems.

In this study, we wanted to assess several relevant environmental and biotic characteristics of ski pistes in comparison to their natural surroundings: first, whether the artificial snow input and its compaction change the snow properties and the soil characteristics. Second, whether there are effects on the structure and diversity of grassland vegetation. Third, we aimed to link our findings to better understand the mechanics of ecosystem changes and ski piste management. To this aim, we addressed the following questions:

- 1) What is the impact of the ski pistes on chemical and physical properties of the snow, on the soil and on the vegetation of mountain grassland ecosystems? Based on previous research, we expected higher snow density (hypothesis H1a), snow pH (H1b) and EC (H1c) on the ski pistes than outside (control), but similar soil temperatures on the ski piste and outside (H2a) due to the natural snow lack. We expected a higher soil pH (H2b) and EC (H2c) on the ski pistes compared to the control. Furthermore, we expected the biomass production (H3a) species richness (H3b) and diversity (H3c) to be higher outside respect inside the ski pistes and differences in the functional groups' proportions (H3d).
- 2) Does the impact on the mountain grassland ecosystems differ between medium (M) and small (S) ski resorts? As S have less intensive management, we expected to find a more contained effect in them compared to M.

## 2. Materials and methods

### 2.1. Study site

The research work begun in the winter 2016–2017, on the pistes of the medium ski resort Ski Center Latemar (Trentino-Alto Adige region). We consider it a medium ski resort because it offers 49 km of ski pistes, whereas the 3 larger ski resorts in South Tyrol (Alta Badia, Plan de Corones and Val Gardena) have 130, 119 and 175 km of pistes, respectively (Dolomiti Superski, 2018). In summer 2017, the study area was extended by including 3 small ski resorts (0.6–7 km of slopes available). We were able to measure snow density, pH, EC and major cations content as well as the soil temperature only in M based on the allowance by the ski area, while the S areas could be integrated in the research only later. Therefore, after the snowmelt, we had full access to all resorts, and all measurements of the soil and of the vegetation were done in all plots of M and S. The snow duration was monitored from web-cams and with the help of photographs and was therefore assessed in all resorts. All ski resorts were established in the 60's and 70's and lie on dolomitic rocks, their elevation goes from 1421 to 2013 m a.s.l. The study area consists of 22 paired plots of 16 m<sup>2</sup> each, divided into the 4 ski resorts (Table 1) and the different measurements taken in each ski resorts are summarized in Table A.1 (Appendix A). At each site, a plot on the grassland of the ski piste was selected and compared with a control plot on the grasslands of the natural surroundings at a distance of 20–60 m from the piste plot, with the same elevation, aspect and slope. The plots were assessed in agreement with the ski area operators, to avoid revegetated areas and the points where terrain modifications had taken place. Moreover, we paid attention to select paired plots where the grazing intensity by cows was similar (the grazers were few and equally distributed). We assessed the average stocking density in the medium ski resort taking into account the information from the forest station of Deutschnofen-Nova Ponente and of the local farmers for the ski pistes in the Trentino part (personal communication) as 0.9 LU/ha (livestock units per hectare). The average stocking density of the small ski resorts 2 and 4 was 0.46 LU/ha and 0.9 LU/ha, respectively (personal communications of the ski resorts president). For the ski resort 3, there was no information available; however, from visual observations it seems to match the situation of the small ski resort 4 indicated previously. The ski piste plots and the control plots differed in the level of mechanical disturbance to which they were exposed.

This mechanical disturbance is due to the snow compaction and soil compression by snow cats and by skiers on the piste. Moreover, mowing is more regular on the ski piste than outside. On the longest slope of the site 1, the “Oberholz”, 5 pairs of plots were established along an altitudinal gradient. All ski pistes are prepared by snow grooming machines. We considered the snow blanket to be formed when it reached the minimum depth necessary for an “Optimal Ski Day”, i.e. 30 cm (Schmude, 2013). Artificial snow was produced starting from different dates according to the ski resort (Table 1).

### 2.2. Ground temperatures and snow cover duration

The snow cover formation was monitored visually on the pistes and on the control plots, with the help of webcams and photographs. The final melt-out date was monitored after the last snowfall (29/04/17), without taking in account snow free periods of the season (27/03/17–28/04/17), and the pistes were considered snow-free as soon as all snow had disappeared from 80% of the ski slope surface (Vonlanthen et al., 2006). HOBO Pendant Temperature Data Logger UA-001-xx (Massachusetts, USA) were used to monitor the soil temperature every hour on the ski pistes and on control plots, from October 2016 to June 2018, only in M. The loggers were placed at 3 cm below the soil surface (Zeidler et al., 2014). There were missing data probably due to soil movements (5/22 data loggers). In the text, we refer to a condition of snow absence-scarcity related to the control plots outside the ski pistes. In fact, outside the ski pistes, there was little natural snow (February and April 2017) or it was completely absent (November–December 2016, January and March 2017).

### 2.3. Snow properties

In the M resort, snow samples were taken in February, March and April 2017. Two cores per plot were collected in all the plots of M using a steel cylinder (volume = 0.5 dm<sup>3</sup>, height = 20 cm) inserted vertically in the snow cover, to sample the first 20 cm of the snowpack. In case of less snow thickness, as in the 50% of the control plots in April, we sampled the centimeters available. The extracted sample of 0.5 dm<sup>3</sup> of volume was immediately weighed with a dynamometer with a precision of ±0.3%. The density of the snow is represented as a volumic mass, defined as the mass of the volume's unit and expressed in kg m<sup>-3</sup> (Cagnati, 2003). The samples were stored in plastic bags and transported

**Table 1**

Study sites in the four ski resorts, (M = medium, S = small) and relevant dates for each site: start of snowmaking, ski season opening and ski season closure. 1-Ski Center Latemar, 2-Skilift Petersberg, 3-Jochgrimm, 4-Skigebiet Villnöss. Each site contains one plot on the piste and one beside the piste.

Ski resort	Piste	Latitude	Longitude	Elevation (m a.s.l.)	Aspect	Start of snowmaking	Ski season opening	Ski season closure
1, M	Oberholz	46°22'55N	11°31'40E	1580	N	04/11/2016	26/11/2016	17/04/2017
1, M	Oberholz	46°22'66N	11°31'95E	1714	NNW	04/11/2016	26/11/2016	17/04/2017
1, M	Oberholz	46°22'48N	11°31'96E	1881	NNW	04/11/2016	26/11/2016	17/04/2017
1, M	Oberholz	46°22'39N	11°33'18E	2020	W	04/11/2016	26/11/2016	17/04/2017
1, M	Oberholz	46°23'64N	11°23'19E	2135	WNW	04/11/2016	26/11/2016	17/04/2017
1, M	Laner	46°21'89N	11°32'38E	1915	W	04/11/2016	26/11/2016	17/04/2017
1, M	Reiter	46°21'18N	11°32'12E	2032	N	04/11/2016	26/11/2016	17/04/2017
1, M	Todesca	46°20'95N	11°32'56E	1946	WSW	04/11/2016	26/11/2016	17/04/2017
1, M	Pala di Santa	46°20'59N	11°32'28E	1928	SSE	04/11/2016	26/11/2016	17/04/2017
1, M	Residenza	46°20'99N	11°33'09E	1940	SW	04/11/2016	26/11/2016	09/04/2017
1, M	5 Nazioni	46°20'74N	11°33'52E	2126	S	04/11/2016	26/11/2016	09/04/2017
1, M	Tresca	46°29'60N	11°19'84E	1860	NNW	04/11/2016	26/11/2016	17/04/2017
1, M	Agnello	46°20'25N	11°32'87E	2038	ENE	04/11/2016	26/11/2016	17/04/2017
1, M	Naturale Agnello	46°20'39N	11°32'78E	1873	NNW	04/11/2016	26/11/2016	17/04/2017
2, S	Petersberg	46°23'60N	11°23'21E	1363	NNW	20/11/2016	02/11/2016	28/03/2017
2, S	Petersberg	46°23'62N	11°23'17E	1384	NNW	20/11/2016	02/11/2016	28/03/2017
3, S	Schwarzhorn	46°20'49N	11°27'24E	2096	N	10/11/2016	08/12/2016	21/04/2017
3, S	Schwarzhorn	46°20'74N	11°27'24E	2013	N	10/11/2016	08/12/2016	21/04/2017
3, S	Weißhorn	46°21'02N	11°26'97E	2075	SE	10/11/2016	08/12/2016	09/04/2017
3, S	Weißhorn	46°20'98N	11°27'02E	2045	SE	10/11/2016	08/12/2016	09/04/2017
4, S	Villnöss	46°37'94N	11°42'87E	1448	N	28/11/2016	08/12/2016	17/03/2017
4, S	Villnöss	46°38'04N	11°42'85E	1421	N	28/11/2016	08/12/2016	17/03/2017

to the lab. Samples were melted and filtered through Whatman filter paper No 42 (125 mm). Subsamples were taken to measure the EC using the HANNA conductivity meter HI 2003-02 (Hanna Instruments, Woonsocket, Rhode Island, USA) and the pH with the Crison pH meter BASIC 20<sup>+</sup> (Crison Instruments, Barcelona, Spain). Other sub-samples were analyzed for the major cations content (Na<sup>+</sup>, NH<sub>4</sub><sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>) using a 930 Compact IC Flex (Metrohm, Switzerland) ion chromatography system.

#### 2.4. Soil analyses

From July to August 2017, soil cores (0.40 diameter by 0.10 m height) were taken at 0–0.50 m depth on the perimeter of all grassland plots to assess the bulk density (BD). At each sample location, two further soil samples of about 100 g were taken at 0–0.30 m depth, transported to the lab, air dried and sieved to <2 mm. 50 g sub-sample were taken to determine the pH with the Crison pH meter BASIC 20<sup>+</sup> (Crison Instruments, Barcelona, Spain), and the EC with the HANNA conductivity meter HI 2003-02 (Hanna Instruments, Woonsocket, Rhode Island, USA).

#### 2.5. Vegetation samples

Between the end of June and the end of August 2017, in all plots in the mountain grasslands of M and S, the percentage cover of each plant species in each plot was estimated. We counted the species number and the Shannon Index of diversity was calculated as  $H = -\sum P_i \ln P_i$ , where  $P_i$  is the relative abundance of species  $i$ . Plants were divided into four functional groups, i.e. grasses (Poaceae) and graminoids (Cyperaceae and Juncaceae) (G), forbs (F), legumes (L), and woody plants (W). The list of species and their classification into functional groups is reported in Appendix B, Table B.1. The vegetation biomass production was calculated by harvesting the biomass at the beginning of July 2017 at peak growth at 3 cm above the ground (Wipf et al., 2005) in an area of 0.5 m<sup>2</sup> in a corner of the experimental plots. The biomass was dried at 70 °C and weighed to obtain the annual productivity of each plot.

#### 2.6. Statistical analyses

As the plant communities were different between the ski resorts and also within ski resorts, a statistical pairwise comparison based on adjacent pairs of controls and ski piste plots was used. For each resort type, (M, S) paired *t*-tests were used to assess the differences in each measured parameter between the ski piste plots with their corresponding control plot outside the piste. Differently, the soil temperature data

was compared with an independent sample *t*-test because the data of the dataloggers of some plots were missing. Prior to comparisons, the data were tested for their normality (Shapiro Wilk test) and for their homogeneity of variance (Levene's test). Data were rank transformed when necessary. To assess in an integrative way both the biotic and abiotic changes observed between control and ski piste plots for each resort type (M, S) a Principal Component Analysis (PCA) was carried out (Zuur et al., 2007). The PCA of M combined all the abiotic information (snow density, snow pH, snow EC, snow cations content, snow duration, soil pH, soil EC, BD) and the vegetation data (vegetation biomass, species' diversity, species' number, grasses' and graminoids' - forbs' - legumes and woody plants' cover) allowing to assess whether there were differences among the pistes and the controls. The same holds true for S, however without the parameters snow density, pH, EC and cations content. Furthermore, the PCA also allowed to quantify the covariation between the abiotic and biotic variables within the ordination space (Zuur et al., 2007). The correlation between the environmental variables and the vegetation data were tested by calculating the Pearson correlation coefficient. In addition, for M, a PCA was run only on the environmental factors in order to compare the piste and the control plots only respect to the abiotic factors. The PCA analyses were done with the software R, version 3.4.0, whereas all other analyses were performed with SPSS, version 25.

### 3. Results

#### 3.1. Soil temperatures, snow duration, and snow properties

Based on our measurements in M, the mean absolute minima of soil temperature under the natural and the artificial snow were similar: −4.11 °C on the piste, and −4.68 under the natural snow (Fig. 1 and Table 2). The mean temperature was significantly lower ( $p < 0.01$ ) on the pistes (−0.45 °C) than on the controls (+0.38 °C), but only in the period where both the plots on the ski pistes and on the controls were covered by snow, after the first snowfall (04/02/17) (Table 2). The temperature registered in the periods before the first snowfall and after the melting of the natural snow did not differ significantly between the two situations.

Judging for both types of resorts, i.e. M and S, the number of the snow-cover days was significantly higher on the ski pistes compared to the controls (Table 3). The snowmelt on the ski slope was delayed in average up to 18 days in the M ski resort and up to 2 days in the S ski resort. As measured in M, snow density, snow pH and EC (Table 4) were all significantly higher both in February and in March ( $p < 0.001$ ) on the ski pistes. The data from April are shown but they were excluded from the comparison because too many control plots lacked the snow cover.

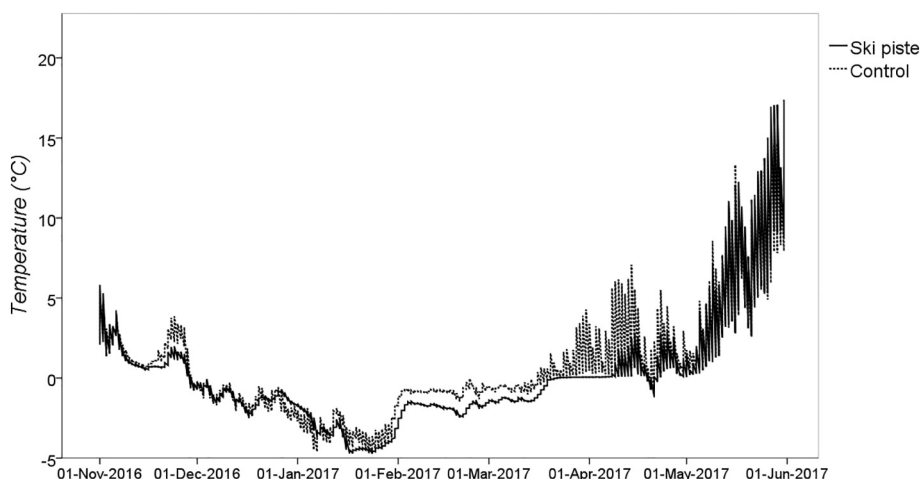


Fig. 1. Measured hour soil temperature at 3 cm depth on the ski pistes and on the control sites. Each line represents an average of 9 and 8 plots, respectively.



**Table 2**

Mean ( $\pm$  standard deviation) absolute minimum of temperature (T), mean daily soil T during the period of artificial snow presence and mean daily soil T without the natural snow cover and under the snow cover, on the ski piste (n = 8) and on the control plots (n = 9), during Winter 2016–2017. Stars indicate significant differences ( $p < 0.01$ ) according to independent *t*-test.

	Absolute minimum of T ( $^{\circ}$ C)	Mean daily soil T ( $^{\circ}$ C) (11-Nov–31-May)	Mean daily soil T ( $^{\circ}$ C) in the period without the natural soil cover (11-Nov–3 Feb)	Mean daily soil T under the snow cover ( $^{\circ}$ C) (4-Feb–8-May)
Piste	−4.11 ( $\pm$ 3.10)	−0.03 ( $\pm$ 3.33)	−1.65 ( $\pm$ 1.82)	−0.45 ( $\pm$ 1.17)**
Control	−4.68 ( $\pm$ 2.66)	0.39 ( $\pm$ 3.07)	−1.44 ( $\pm$ 1.93)	0.38 ( $\pm$ 1.20)

The *t*-paired test also showed that  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  concentrations, which were measured in M, were higher in the snow on the ski piste compared to the control (Table 5).

### 3.2. Soil properties

In both resort types (M and S), soil BD did not differ between the treatments (data not shown). Soil pH and EC were significantly higher ( $p < 0.01$  and  $p < 0.05$ , respectively) on the ski piste in M (Fig. 2a, b). Also in S, soil pH was significantly higher on the ski piste ( $p < 0.01$ ), whereas soil EC did not differ.

### 3.3. Biomass production, species richness and diversity, functional group composition

The biomass production was significantly lower on the ski piste plots showing an average reduction of 35.6% compared to the control plots in M (Fig. 2c). In S, however, there were no significant differences neither in the biomass production nor in the species richness between ski piste plots and control plots (Fig. 2c, d). In this resort type, 68 species were detected in the controls (n = 8) and 71 on the ski pistes' plots (n = 8). In the control plots of M (n = 14), a total of 97 plant species were recorded, whereas on the ski pistes' plots (n = 14) a total of 79 plant species were present. This reflected a significant difference in species number per plot with an average of 23.5% lower richness on the ski pistes in M respect to the controls (Fig. 2d). The functional group composition was largely affected by the ski piste in both the ski resorts types, with a uniform pattern in all the plots: higher presence of legumes (as *Trifolium pratense*, *Trifolium repens*, *Lotus corniculatus*) and lower presence of woody plants (such as *Vaccinium myrtillus*, *Vaccinium vitis idaea* and *Juniperus communis*) on the ski piste than on the control plots. In M, grasses (represented mainly by *Phleum pratense*, *Avenella flexuosa* and *Deschampsia caespitosa*) and graminoids were also less abundant on the ski pistes; although the data were only marginally significant ( $p = 0.051$ ), the trend was clear (mean G controls =  $59.2 \pm 5.9\%$ , mean G pistes =  $46.3 \pm 4.2\%$ ; Fig. 3). The proportion of forbs, whose most representative species were *Ranunculus acris*, *Alchemilla glabra* and *Achillea millefolium*, and the Shannon's Index of diversity did not change between the ski pistes and the control plots, in none of the ski resort types.

### 3.4. Differences of ski pistes vs controls and of medium vs small ski resorts

For M, the PCA analysis indicated that the first two dimensions explained 53% of the observed difference between ski pistes and control plots (Fig. 4). The first dimension highly correlated with snow duration, snow pH and snow EC, whereas the second dimension correlated with

the forbs composition and with the soil pH and EC. The PCA revealed that legumes, in both ski resorts types, were related mainly to the snow duration and in particularly in S (Fig. 5), to the soil pH. In M, physical and chemical snow properties were analyzed, and it can be observed that legumes were more abundant where the cations' input and the snow duration are higher, i.e. on the ski piste. The relation soil pH–legumes' cover is confirmed in M by the Pearson's correlation coefficient: ( $r = 0.474$ ,  $p < 0.05$ , Fig. 6 and Appendix D, Table D.1). The correlation coefficient also showed the inverse effect of the increasing pH on the grasses' and graminoids' cover ( $r = -0.399$ ,  $p < 0.05$ , Appendix D, Table D.1).

The control plot 10 (marked with an asterisk in Fig. 4 and in Fig. C1) showed intermediate values of all the parameters respect to the other pistes, where the differentiation between ski pistes plots and controls was clear. Direct observation of the skiers' behavior on this slope explained the result, because this is a quite wide ski piste used mainly by snowboarders, who move a big amount of snow from the piste to the outside.

For M, a second PCA was run only with environmental parameters to assess the relative contributions of snow and soil physico-chemical factors to differentiate the ski slope plots and the control plots (Appendix C, Fig. C.1). The first dimension explained 53% of the variance, and it was highly correlated with snow pH, snow EC and snow  $\text{Ca}^{2+}$  content, whereas the second dimension was highly correlated with soil pH and EC, and explained 18% of the variation.

The PCA for S areas (Fig. 5) showed different results when all the parameters were run together: two dimensions explained 48% of the variation between the ski pistes and the control plots; the first dimension highly correlated with the plant biomass production and with the composition of the woody species. The second dimension correlated with the bulk density and with the composition of grasses and graminoids.

## 4. Discussion

### 4.1. Soil temperature under artificial and natural snow under long skiing season (M)

The soil below the ski piste was on average cooler than the soil below the natural snow layer as it has been reported in other studies (Rixen et al., 2008a). However, this difference is true only for the period of natural snowfall, which ranged from February, 4th to May 8th. In fact, in a winter of snow scarcity as in the one of 2016–2017, novel situations

**Table 3**

Mean ( $\pm$  standard deviation) snow days number on the ski pistes and on the controls in the medium (M) (n = 14) and small (S) (n = 8) ski resorts. Stars indicate significant differences ( $p < 0.001$ ) according to paired *t*-test.

	Snow days	
	Piste	Control
M	194.42 ( $\pm$ 1.74)***	91.78 ( $\pm$ 0.43)
S	132.84 ( $\pm$ 3.76)***	93 ( $\pm$ 0.37)

**Table 4**

Mean values ( $\pm$  standard deviation) of snow density (SD), snow pH, snow electrical conductivity (EC) in February (Feb), March (Mar) and April (Apr) 2017, on the ski pistes (n = 14) and on the control plots (n = 14) in the medium ski resort. For every plot, two measurements per month were taken. Stars indicate significant differences ( $p < 0.001$ ) according to paired *t*-test.

	Month	Piste	Control
SD	Feb	496.32 ( $\pm$ 11.25)***	158.79 ( $\pm$ 20.89)
	Mar	494.19 ( $\pm$ 11.45)***	219.19 ( $\pm$ 16.44)
	Apr	533.66 ( $\pm$ 38.48)	–
pH	Feb	9.45 ( $\pm$ 0.12)***	6.37 ( $\pm$ 0.33)
	Mar	9.20 ( $\pm$ 0.21)***	5.98 ( $\pm$ 0.12)
	Apr	8.56 ( $\pm$ 0.13)	–
EC	Feb	183.90 ( $\pm$ 19.54)***	39.67 ( $\pm$ 18.44)
	Mar	133.54 ( $\pm$ 19.93)***	7.98 ( $\pm$ 0.76)
	Apr	41.14 ( $\pm$ 3.78)	–

**Table 5**

Mean values ( $\pm$  standard deviation) of the cation contents ( $\text{mg l}^{-1}$ ) of the melted snow sampled on the ski pistes ( $n = 14$ ) and on the controls ( $n = 14$ ) in the medium ski resort. For each plot, two replicates sampled in February 2017 were analyzed. Stars indicate significant differences (\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ ) according to paired  $t$ -test.

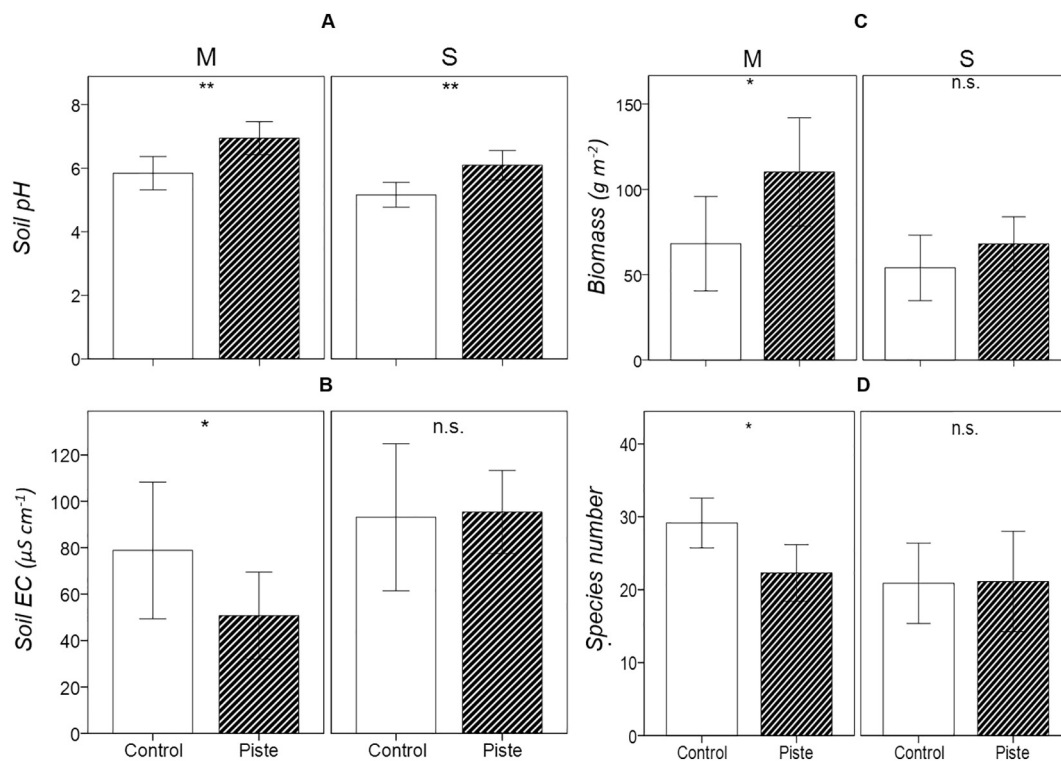
	Piste	Control
$\text{Na}^+$	2.12 ( $\pm 0.21$ )*	1.51 ( $\pm 0.29$ )
$\text{NH}_4^+$	0.42 ( $\pm 0.04$ )	0.62 ( $\pm 0.09$ )
$\text{K}^+$	0.49 ( $\pm 0.06$ )*	0.28 ( $\pm 0.06$ )
$\text{Ca}^{2+}$	28.94 ( $\pm 3.46$ ***)	6.71 ( $\pm 2.96$ )
$\text{Mg}^{2+}$	8.02 ( $\pm 1.02$ **)	1.97 ( $\pm 1.08$ )

appeared. The lacking natural snow cover from the mid of November to the beginning of February led to similarly cold temperatures on the piste and outside. However, in our study the main temperature differences were registered during the winter season (beginning of February to the end of March) and not at the beginning of the growing season (from April onwards, Fig. 1), when warmer temperatures are necessary for the plants to begin photosynthesis and to form their new tissues (Körner, 2003). On the other hand, we found that the scarcity of snow outside the ski piste during winter may expose the soil to low temperatures (if there are low temperatures) similar to a denser and compacted artificial snow cover: the minimum temperatures reached by the ground were similar. This is a novel condition that distances itself from the previous studies (Rixen, 2013 and references therein), where the natural snow was usually present outside the pistes. Our results represent an example of the possible future (and more frequent) climate-change scenarios (IPCC, 2014).

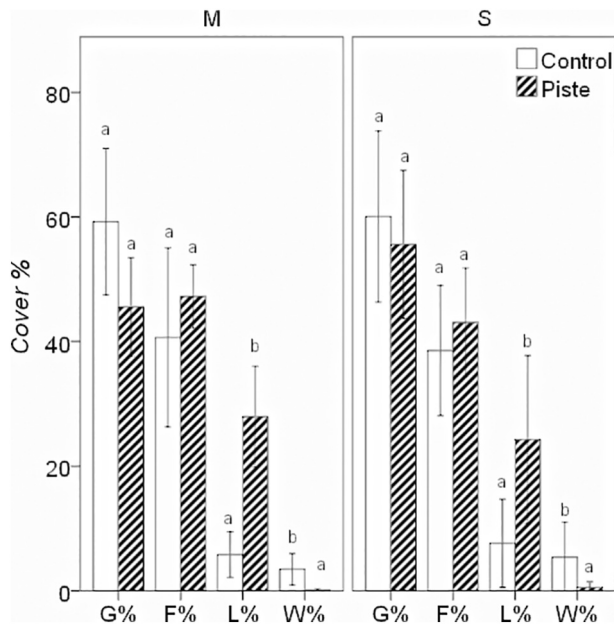
#### 4.2. Ski-piste effect on vegetation

Our results from the M resort confirmed that besides the snow duration also the pH and EC of the snow as well as of the soil were related to vegetation differences between the piste and outside. Snow duration

was 30% longer on the ski pistes compared to the controls in the S resorts. However, in the M resort the snow duration was even twice as much on the ski pistes compared to the controls. Although artificial snow may protect plants from frost and from mechanical damage, it delays growth and germination. This fact might also play a role for the higher presence in both M and S ski resorts of more competitive species on the ski slope such as *Trifolium repens*, *Trifolium pratense*, and *Taraxacum* sp. In addition, we found in M that with increasing soil pH the legumes' cover increased, whereas the grasses' and graminoids' cover decreased. This result agrees with the findings of Kammer and Hegg (1990) and of Rixen et al. (2002), who also found a widespread presence of nutrient-indicating plants such as *T. repens* on the ski slope, and a lower grasses' and graminoids' cover. Most probably, the higher EC and pH in the snow influenced the EC and pH in the soil (Kammer and Hegg, 1990; Freppaz et al., 2013). In fact, they both are higher on the ski slope in M, and the soil pH is higher on the ski piste also in S. Higher EC could reflect the cation input that comes from the artificial snow ( $\text{Ca}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ) besides the higher snow density (Farzaneh et al., 2004). Our study sites lie on dolomitic soils, where the water used for snowmaking is pumped from dolomitic rivers and from water reservoirs, which are filled with dolomitic and with running water. Thus, it seems likely that the high  $\text{Ca}^{2+}$  content is responsible for the pH alteration. Vonlanthen et al. (2006) reported that species richness in alpine zones is highly correlated firstly with the maximum temperature and secondly with the soil pH, there is a unimodal relationship between species number and pH. Very high pH levels could affect the species number and the vegetation composition because pH enhances the formation of complexes that make some elements unavailable for plants, as the micronutrients iron (Fe), manganese (Mn), and zinc (Zn) (Wang et al., 2018). For example, it was reported by Bravo et al. (2017) that the bioaccumulation of calcium (Ca), Mn, Zn and copper (Cu) decreased in the leaves of vine plants with pH values higher than 7. Scheffer and Schachtschabel (2002) showed that above pH of 5.7, the availability of Mn drops. In the same way, a shortage of Fe

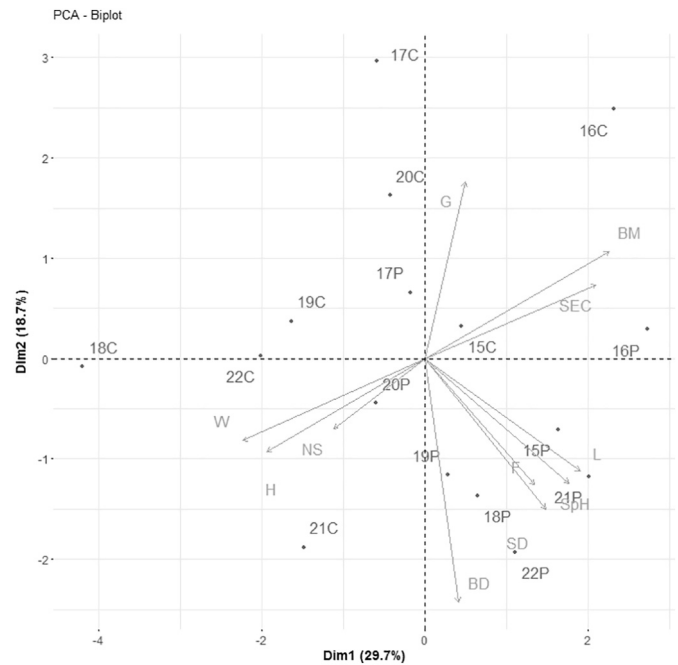


**Fig. 2.** Soil pH (A), soil electrical conductivity (EC) (B), biomass production (C) and species' number (D) per plot on the controls and on the ski pistes in the medium (M), ( $n = 14$ ) and small (S), ( $n = 8$ ) ski resorts. Bars are the means of the plots and error bars represent  $\pm 2$  SE of the mean. Stars indicate significant differences (\* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ ) according to paired  $t$ -test.



**Fig. 3.** Percentage cover of the four functional groups (F: forbs; G: grasses and graminoids; L: legumes; W: woody plants) on the controls and on the ski pistes in the medium (M), (n = 14) and small (S), (n = 8) ski resorts. Bars are the means and error bars represent  $\pm 2$  SE of the mean. Different letters indicate statistical significant differences between controls and ski pistes for every single group ( $p < 0.05$ ) according to paired *t*-test.

availability comes along with pH higher than 7 and the amount of available Zn is very low in case of pH values higher than 6. By using snow additives in an experiment, Rixen et al. (2008b) found evidence for ammonium nitrate to affect biomass production, but not for calcium-rich water, at least in the short-term. In the long-term, as on a ski piste, Chytrý et al. (2003) state that soil pH and  $\text{Ca}^{2+}$  are two of



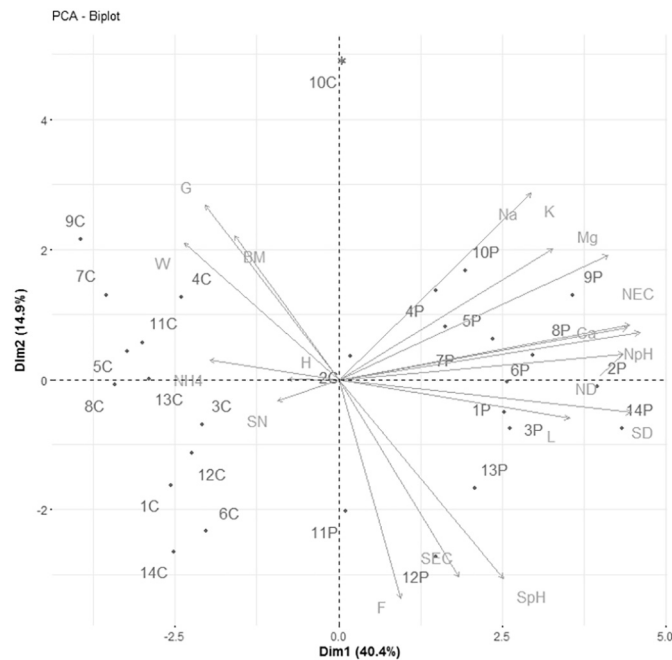
**Fig. 5.** Biplot based on principal component analysis of the plots in the small ski resorts on the ski pistes (P), control plots (C), vegetation data (BM = biomass; H = Shannon Index; SN = species' number; G = grasses' and graminoids' cover; F = forbs' cover; L = legumes' cover; W = woody plants' cover) and environmental factors (SD = snow duration; SpH = soil pH; SEC = soil electrical conductivity; BD = bulk density).

the most relevant parameters that determine species composition and diversity, because plants are adapted either to low or to high pH soils. The lower biomass production and the lower species number observed in our study on the mountain grassland of the ski slope than on the controls in M could then be a consequence of the shorter growing season and of the mechanical disturbance, but also of the increasing  $\text{Ca}^{2+}$  content and pH.

Another possible explanation of the higher presence of legumes on the ski slopes is that they can profit of a lower competition with shrubs (Wipf et al., 2005), which are less abundant on the ski pistes (Fig. 3). In fact, woody plants may be more susceptible to the mechanical damage caused by the skiers and, especially, by the grooming machines (Kangas et al., 2009). Furthermore, late summer mowing is a common practice in the study areas because there is an agreement with the local farmers, who are allowed to mow the meadows to make hay and because ski runs need to be mowed to reduce the amount of snow needed in winter to cover the ski pistes. This habit is then more frequent on the grasslands of the ski slope (once every year) than in the surroundings where it is less regular. Moreover, it may also hinder the spread of the woody plants more strongly on the pistes. Consequently, their development is interrupted every year by the mechanical disturbances, precluding the natural succession to occur. Within the legumes, instead, the presence of the genus *Trifolium* causes the legumes' biomass production to increase, as it occurred in a Körner's work with *T. pratense* (Körner et al., 2008). In fact, both *T. repens* and *T. pratense*, probably because of their nutrient demand, can spread easily on the ski slope. In conclusion, in our study, the disturbance caused by the ski piste may interrupt the succession and create a new ecosystem.

#### 4.3. Medium vs small ski resorts

In the small ski resorts, the comparison of the mountain grassland vegetation inside the ski slopes and outside them showed smaller differences compared to the effects recorded in the medium resort. In specific, in S resorts species richness and productivity were not altered like in M resort. Compared to M, S resorts have fewer resources (in terms of



**Fig. 4.** Biplot based on principal component analysis of the plots in the medium ski resort on the ski pistes (P), control plots (C), vegetation data (BM = biomass; H = Shannon Index; SN = species' number; G = grasses' and graminoids' cover; F = forbs' cover; L = legumes' cover; W = woody plants' cover) and environmental factors (ND = snow density; NpH = snow pH; NEC = snow electrical conductivity; SD = snow duration; SpH = soil pH; SEC = soil electrical conductivity; BD = bulk density).

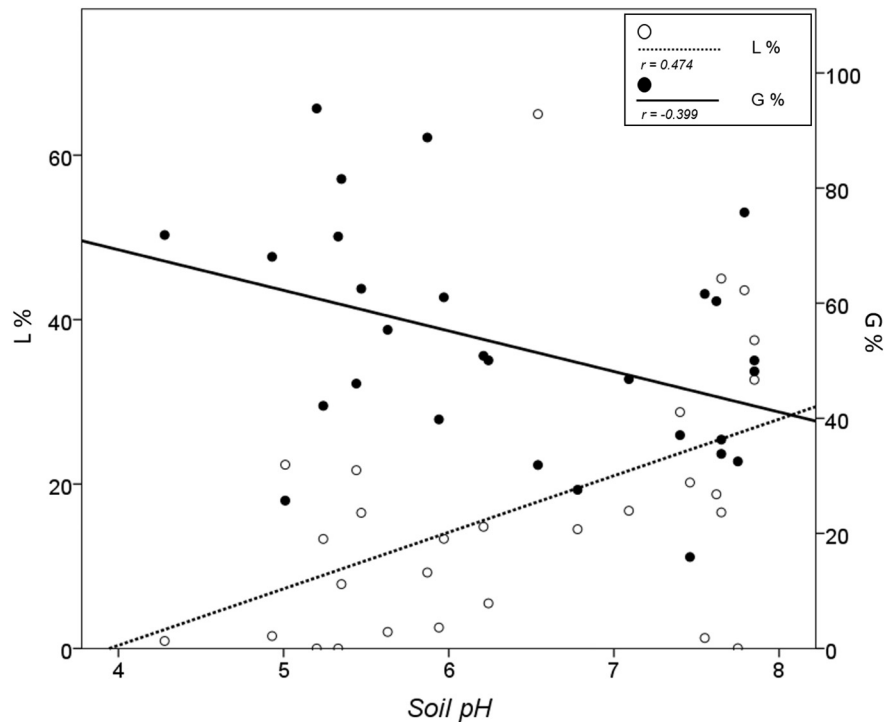


Fig. 6. The relationships between the soil pH and the grasses' and graminoids' (G%) - and legumes' (L%) cover in the medium ski resort ( $n = 28$ ).

money and labour) to extend the ski season and this is probably the reason why their impact is reduced: a shorter ski season demands lower artificial snow use and therefore a less delayed snow melting time and a lower cations input in the soil. Although the pH was altered even in S, it was a unit less basic than in M. It is also important to consider that S are addressed to a more restricted clientele, and the number of skiers also greatly affects the amount of artificial snow needed for an “optimal ski day”, since “an average skier displaces 907 kg (1 ton) of snow each day” (Mergen, 1997, reported by Gross and Winiwarter, 2015). These results confirm our hypothesis that ski management practices affect mountain grassland vegetation, but the effects depend also on the ski resort's dimension and organization. In fact, even the effects observed in M are restrained as compared to other studies performed in bigger ski resorts (Kammer, 2002; Wipf et al., 2005). In these bigger resorts, the species diversity was reduced on the ski pistes, whereas in our study we did not find a lower diversity neither in M nor in S on the ski slopes. Thus, our results indicated that constraining the touristic season between December and March, as the small ski resorts in our study do, has a lower impact on the ecosystem and is therefore in relation more sustainable, considering that climate models predict that with 4 °C warming only the 30% of the ski areas will still have natural snow (Abegg et al., 2007). If we take into account that snow governs the species distribution in snow-covered ecosystems (Walker et al., 2001) and protects plants from low temperatures and from solar radiation (Körner, 2003), then artificial snow may also compensate the related negative effects due to the snow lack to a certain extent (Steinbauer et al., 2018). Our findings revealed that only in the small ski resorts the use of the artificial snow affected neither the species richness nor the biomass production. This suggests that they could be considered for a sustainable management of mountain grasslands.

#### 4.4. Limitations of our study

In mountain grasslands, an array of factors that act in concert shape the impact of ski piste management on vegetation. In field studies, we cannot isolate the effects of those different factors acting together that contribute to the observed differences in vegetation. We think that

experiments under controlled conditions should be more appropriate to identify the cause-effect relations on the mentioned issues. Nevertheless, even in the best control conditions experiment, the natural conditions cannot be mimicked and predicted. Our study was of short duration, thus, extending the study for more years could give a better understanding on the mechanisms acting on the development of the vegetation on the ski piste. More data to compare the physico-chemical characteristics of the snow and the temperatures below it in small resorts could have been useful. However, also the S systems are in dolomite areas and their artificial snow is produced in the same way. Moreover, the climatic conditions and the resulting situation of snow scarcity are the same in M and S, making M a standard case regarding the effects of snow lack on soil temperature. Furthermore, our study addresses many of the possible grassland ecosystem- impacting factors operating on a ski piste in a year of snow scarcity. Future investigations on the impact of the increasing use of artificial snow on vegetation are needed, not only for the changing climate, but also because the needs of the skiers are changing. They require a more intensive preparation of the ski slopes than in the past, the new market demands require an optimal snow compaction and laying, which preferably does not have to be natural. Therefore, snow-melting times are expected to be more and more delayed and it is important to understand the effects in the long term. In addition to the phenological aspects, the effects on the ecophysiology of plants grown under this type of snow should also be deepened. Moreover, future research should be designed to address the balance between positive and negative impacts of artificial snow cover of mountain grasslands with snow cover.

#### 5. Conclusions

The most important factors affecting the observed differences in vegetation between pistes and controls were snow duration, snow and soil chemical properties. Ski management practices act on grassland vegetation, but the effects differ between medium and small ski resorts, and are proportional to the intensity of the ski slope preparation of the ski resort. The differences rely probably on the amount of artificial snow used, which determines the snow compaction and the duration of the



snow cover. In fact, using less amount of artificial snow decreases the minerals input and so it may prevent big shifts in the soil pH from acidic to basic. The soil temperatures revealed that the snow scarcity and the snow lack led to low temperatures similar to those reached under the compacted artificial snow exposing mountain grasslands to new challenges.

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